

# Horizons as Dimensional Interfaces: A Relational Framework for Source–Geometry Coupling, Interspace, and Ordered Composition

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## Abstract

We develop a relational framework in which boundaries are treated not as passive separations, but as interfaces whose physical character depends on the transformation rules imposed across them. In the ideal limit, an interface reduces to a smooth, lossless coordinate identification that preserves coherent motion and supports transport-like or oscillatory dynamics without dissipation. More generally, interfaces can govern source, geometry, or their mutual evolution rather than merely transmitting them across a boundary. The framework classifies such behavior along two complementary axes: *dynamical regimes* and *coupling classes*. Dynamically, interfaces can preserve, redirect, dissipate, thermalize, or otherwise transform relational evolution. In coupling structure, they can relate geometry-to-geometry, source-to-source, or source-to-geometry degrees of freedom. Beyond isolated interfaces, the framework also treats relational evolution as an ordered composition of relational stages—formalized here as *conditional relational pipelines*—whose cumulative organization may generate nontrivial traversal structure. In this extended view, interspace is not treated as a pre-existing interval or neutral passage, but as the relational structure induced by composed interfaces. Depending on how such compositions are arranged, they may preserve source structure, generate cumulative transformation, or encode conditional relational behavior that shapes admissibility, accessibility, and effective traversal outcome. Rather than presuming immediate physical realizability for all such regimes, the framework provides a structured relational language for analyzing how different interface assumptions generate distinct classes of behavior. More

broadly, the framework treats the interface as a fundamental relational object for organizing transport, transformation, and state-dependent evolution across physical systems.

**Keywords:** relational interfaces; source–geometry coupling; interspace; ordered composition; conditional relational pipelines; transition structure

## 1 Introduction

Boundaries in physical systems are typically treated as passive separations: surfaces, coordinate identifications, or matching conditions across which fields, particles, or geometries are transferred or constrained [1, 2]. While this treatment is adequate in regimes where the boundary does not significantly alter the structure of traversing quantities, it becomes insufficient in settings involving structured interactions. In the presence of extended sources, nonuniform media, frame mismatch, or dissipative structure, the structure associated with the boundary can influence which features are preserved, which are transformed, and which forms of propagation or coupling remain admissible [3, 4]. In such cases, the boundary is not merely a separator but an active participant in the relational evolution of the system.

This work develops a relational framework in which such boundaries are treated instead as *interfaces*: structured transition objects whose physical behavior depends on the transformation rules imposed across them. In the idealized limit, an interface reduces to a smooth, lossless coordinate identification that preserves coherent motion and supports transport-like or oscillatory dynamics without dissipation. More generally, however, an interface need not merely transmit traversing structure, but can govern how source, geometry, or their mutual coupling evolve across a transition. In this broader sense, an interface is treated not simply as a separator between regions, but as an active relational operator whose role depends on what is preserved, transformed, or reconfigured across it. Accordingly, boundary-like supports may be treated as *horizons* in cases where their physical significance arises not merely from delimitation, but from the interface structure defined across them.

HDIF is organized around two complementary classification axes. The first is coupling class, which characterizes what kinds of degrees of freedom are related across an interface, including geometry-to-geometry, source-to-source, and source-to-geometry couplings. The second is dynamical regimes, which characterizes how an interface modifies relational evolution, including whether traversing structure is preserved, redirected, dissipated, thermalized, or otherwise transformed. Taken together, these axes distinguish both what an interface acts upon and how it acts.

Such a relational and emergent framing has precedents in foundational physics, where system behavior is understood to depend on the organization of relations rather than on isolated elements alone [5, 6]. In the present work, this perspective is developed into a structured framework for classifying and composing interface-mediated relational evolution. Beyond isolated boundaries,

this viewpoint extends naturally to ordered compositions of interface-mediated structure. In this extended setting, the framework gives rise to organized sequential architectures—formalized here as *conditional relational pipelines*—in which relational outcomes depend on composition, context, and transformation order. Within such architectures, interspace is not treated as an empty passage or pre-given interval through which traversal subsequently occurs. Rather, it is understood as the relational structure induced by composed interfaces themselves. In more structured realizations, such composition may generate an emergent traversal architecture whose accessibility, admissibility, and effective behavior depend on how the relevant interfaces are arranged and related. Interface behavior may therefore depend not only on a single local transition map, but on the cumulative relational organization of sequential interface structure. The aim of the present work is not to presume immediate physical realizability for all such regimes, but to develop a general relational language for studying how interface structure organizes transport, coupling, transformation, and state-dependent evolution across physical systems.

More broadly, the framework also motivates a sharper class of future questions concerning whether transition-supports, interfaces, or horizon-like structures may provide a useful setting for probing the admissibility and observable consequences of deeper source–geometry response laws.

In summary, the present work introduces three central contributions: (1) the formulation of the interface as a rule-bearing relational object rather than a passive boundary, (2) a two-axis classification of interface behavior in terms of coupling classes and dynamical regimes, and (3) the development of conditional relational pipelines as ordered architectures governing composition-sensitive relational evolution. Together, these elements provide a unified relational framework for analyzing transition systems in which traversal behavior cannot be reduced to passive boundary crossing alone.

## 2 Foundational Definition: The Interface as a Relational Object

### 2.1 Definition of an Interface

In this framework, an *interface* is defined as a rule-governed relational structure that relates, transforms, or constrains states, coordinates, sources, or geometries across a boundary. Unlike a boundary, which serves primarily as a geometric or topological separator, an interface specifies how relational structure is mapped, preserved, or modified across its defining support conditions.

An interface is therefore not characterized solely by its location, but by the transformation rules it imposes. These rules determine how quantities or structures on one side are related to those on the other, including whether they are preserved, reoriented, dissipated, or otherwise transformed during traversal. In the ideal limit, an interface may reduce to a smooth coordinate identification that preserves all relevant structure. In more general settings, however, it may

introduce asymmetry, nonlinearity, dissipation, or history-dependent response. More generally, interface structure may condition not only how traversal proceeds, but also which forms of relational transformation are locally admissible across the interface.

## 2.2 Boundary vs Interface

It is important to distinguish between the notions of a boundary and an interface.

A *boundary* refers to a location or surface that separates regions of space, spacetime, or state space. It may be defined geometrically, topologically, or by constraint conditions, but does not, by itself, specify how relational structure is transferred or transformed across it.

An *interface*, by contrast, is a transformation-bearing object. It encodes how relational structure is transferred, constrained, or transformed across its defining support. While a boundary may exist without specifying a transformation rule, an interface is defined precisely by such rules [2, 3].

In this sense, a boundary can be viewed as the *support* of an interface, while the interface itself is the relational structure that acts across it.

In the present framework, the term *horizon* is used in a generalized relational sense to denote a transition-support across which dimensional, geometric, or source-dependent interface structure may be defined. A horizon, in this usage, need not refer exclusively to a causal boundary in the relativistic sense, but more broadly to any delimiting support whose significance arises from the interface relations it sustains.

## 2.3 Matching and Mixing

Interfaces may operate in fundamentally different ways depending on how relational structure is handled across them. A useful distinction is between *matching* and *mixing*.

**Matching** refers to interfaces that preserve compatibility or continuity across the interface support. In this case, relational structure is aligned or identified across the interface without substantive alteration. Examples include smooth coordinate identifications, continuity conditions in field theory, or lossless mappings between equivalent geometries.

**Mixing**, by contrast, refers to interfaces that actively transform relational structure. This may include blending, recombination, dissipation, or reconfiguration of source states or degrees of freedom. In such cases, the interface does not merely align structures, but modifies them according to the transformation rules it encodes.

This distinction provides a preliminary behavioral axis for understanding when an interface acts as a conservative identification versus a transformation-bearing structure, and anticipates the fuller classification developed in later sections. More generally, all interface regimes presuppose some relational coupling through which behavior is enacted. Coupling class identifies the sectors linked by the interface, whereas dynamical regime characterizes the effective manner in

which that linkage manifests. The former constrains the latter without uniquely determining it.

## 2.4 Preservation, Transformation, and Historical Encoding

A central organizing concern of the framework is to identify which aspects of relational structure a given interface preserves, redirects, dissipates, or renders dependent on prior relational states.

This perspective shifts attention from the mere existence of a boundary to the effective consequences of interface action. Depending on its structure, an interface may preserve coherence or conserved quantities, redirect propagation, dissipate energy or organization into additional degrees of freedom, or retain dependence on prior states, thereby producing memory-bearing or path-dependent behavior [9, 10]. These possibilities are not mutually exclusive and may coexist within a single interface. The classification of coupling classes and dynamical regimes in the following sections builds on this diagnostic question by distinguishing both what sectors are linked and how their effective evolution is conditioned.

## 3 Coupling Class of Interfaces

### 3.1 Coupling Class as a Structural Characterization

The first principal axis of HDIF is the *coupling class*, which characterizes what kinds of degrees of freedom are related across an interface. Whereas the dynamical regime describes *how* an interface acts, coupling class describes *what* it acts upon. This distinction is essential: two interfaces may exhibit similar dynamical behavior while operating on fundamentally different kinds of relational structure.

Coupling class is therefore a *structural characterization* of interface action. It identifies the sectors of relational organization that are brought into correspondence, transformation, or constraint through interface structure. In the present framework, the minimal coupling classes are geometry-to-geometry, source-to-source, and source-to-geometry.

Although analytically distinct, coupling classes and dynamical regimes are often related in practice. The relational sectors brought into interaction by an interface constrain which modes of preservation, transformation, dissipation, or memory may arise, though they do not uniquely determine them. Coupling class specifies what is coupled, whereas dynamical regime, introduced in the next section, characterizes how that coupling behaves.

### 3.2 Geometry-to-Geometry Interfaces

A *geometry-to-geometry* interface relates geometric or coordinate structure across an interface support. In this subclass, the primary role of the interface is to map one spatial, spacetime, or metric organization onto another. The relevant

relational content is therefore geometric in character, including coordinate identification, geometric continuity, curvature matching, dimensional transition, or other structural relations between geometric configurations.

In the simplest limit, geometry-to-geometry interfaces reduce to smooth coordinate identifications or conservative geometric gluing maps. More generally, however, they may involve discontinuity, distortion, frame mismatch, or nontrivial transformation between geometrically distinct configurations. This subclass is therefore central whenever the interface acts primarily on how space, spacetime, or geometric organization is related through its defining relational structure.

### 3.3 Source-to-Source Interfaces

A *source-to-source* interface relates source structure across a transition. In this subclass, the interface acts primarily on the internal organization, state, or composition of traversing material, energetic, informational, or otherwise source-bearing content. The interface therefore governs how source structure is preserved, mixed, filtered, recombined, or transformed across passage.

This subclass includes cases in which the interface acts on the traversing system without substantially altering the underlying geometric organization associated with the interface support. Examples may include state-selective filtering, dissipative transformation, compositional reconfiguration, or source-dependent memory effects. Source-to-source coupling is therefore the natural subclass whenever the interface primarily reorganizes what passes through it rather than the geometric structure relative to which traversal is defined.

### 3.4 Source-to-Geometry Interfaces

A *source-to-geometry* interface relates source structure and geometric structure through interface action. In this subclass, the interface does not act solely within one sector, but instead mediates how source properties influence geometry, how geometry conditions source evolution, or how the two are co-transformed during traversal.

This coupling subclass is especially important in regimes where geometric organization cannot be treated independently of the source, or where the interface itself acts as a transducer between source-bearing and geometric degrees of freedom. Such interfaces may encode source-conditioned geometry, geometry-conditioned source evolution, or more general bidirectional coupling between the two. Source-to-geometry interfaces therefore occupy a central role in any framework where geometry is not treated as a purely passive background.

### 3.5 Composite and Nested Coupling Structures

Coupling classes, like the dynamical regimes discussed later, should not be treated as rigidly isolated categories. A single interface may simultaneously exhibit geometry-to-geometry matching, source-to-source transformation, and source-to-geometry coupling at different levels of description. In more complex

systems, one coupling subclass may dominate the macroscopic behavior while another governs the microscopic or emergent structure.

For this reason, coupling class is best understood as a classification of dominant relational sectors rather than a claim of exclusive ontological separation. This allows HDIF to accommodate interfaces that are layered, multiscale, or internally composite without forcing all physically relevant cases into a single primitive subclass.

## 4 Dynamical Regimes of Interfaces

### 4.1 Regime as an Effective Characterization

The second principal axis of HDIF is *dynamical regime*, which characterizes how an interface acts upon traversing relational structure. A dynamical regime does not specify what kinds of degrees of freedom are being related—that role belongs to coupling class—but instead describes the effective mode by which the interface preserves, redirects, transforms, dissipates, or otherwise conditions relational evolution.

This notion is intended as an *effective characterization* rather than a microscopic derivation. That is, an interface may be classified by the qualitative form of its action without requiring a complete underlying physical model at the outset. In this sense, regime describes how an interface behaves as a relational operator, independent of the specific physical realization through which that behavior is implemented.

### 4.2 Conservative and Preservative Regimes

The simplest dynamical regime is one in which an interface preserves the relevant relational structure across traversal. In this case, the interface acts as a conservative identification or transfer rule: traversing quantities retain their essential organization, coherence, or continuity without substantive loss or reconfiguration.

This regime includes idealized smooth coordinate identifications, lossless matching conditions, and conservative transition maps in which the interface serves primarily to transmit rather than alter structure. More generally, preservative behavior may also include piecewise or segmented interfaces so long as the effective relational content remains conserved across traversal. Such interfaces are therefore *matching-dominant*, even when their geometric realization is nontrivial.

### 4.3 Transformative and Nonconservative Regimes

More general interfaces need not preserve relational structure exactly. Instead, they may redirect, distort, dissipate, thermalize, mix, or otherwise transform traversing states during transition. In such cases, the interface acts not merely as a conservative identification, but as a transformation-bearing structure whose rules modify the effective evolution of the source or geometry passing through it.

Transformative regimes may arise from asymmetry, nonuniformity, frame mismatch, environmental coupling, nonlinear response, or additional relational structure encoded in the interface itself. The resulting behavior may include energy loss, coherence degradation, state mixing, geometric distortion, or re-orientation of propagation. Such interfaces are therefore *mixing-dominant*, in the sense that they alter rather than simply preserve the relational content of traversal.

#### 4.4 Memory-Bearing and History-Dependent Regimes

Another important dynamical regime arises when interface behavior depends not only on the instantaneous state of traversal, but also on prior states, prior crossings, or previously encoded relational conditions. In such cases, the interface exhibits *memory-bearing* or *history-dependent* behavior.

Such regimes may arise through accumulated state, delayed interaction, adaptive response, prior configuration, or retained relational history. Their effective behavior may be path-dependent, non-Markovian, or hysteretic in character, depending on the physical realization [9, 10, 11].

Importantly, memory-bearing regimes need not be purely dissipative: an interface may preserve certain structures while still retaining a historical imprint that influences future traversal. In this sense, historical encoding constitutes a distinct dynamical feature rather than merely a subtype of loss or transformation.

#### 4.5 Hybrid and Composite Regimes

The preceding regimes should not be understood as mutually exclusive or rigidly disjoint categories. A single interface may preserve some aspects of relational structure while dissipating others, or may behave conservatively in one degree of freedom while remaining memory-bearing or transformative in another. Likewise, regimes may vary with scale, state, environmental context, or traversal history.

For this reason, a dynamical regime is best understood as a structured classification of dominant interface behavior rather than an exhaustive partition into isolated types. This allows HDIF to accommodate interfaces that are idealized, mixed, nonlinear, context-sensitive, or hierarchically layered without requiring each physically relevant case to be forced into a single primitive category.

### 5 The Interspace as an Emergent Relational Structure

#### 5.1 Interspace as More Than Empty Passage

Once interfaces are treated as active relational structures rather than passive boundaries, it becomes necessary to reconsider the nature of what is often taken to be the domain between them. In conventional treatments, such an interval is

typically assumed to function as a neutral passage through which a source, field, or geometry propagates until encountering the next boundary.

Within HDIF, however, interspace is not understood as a pre-existing region or interval separating interfaces. Rather, it is defined as the relational structure induced by their ordered composition. In this sense, interspace does not exist independently of interface architecture; it is the effective traversal domain generated by the way interfaces are arranged and related.

Its effective character is therefore not determined by geometric separation alone, but by the relational conditions enacted through composition. In the stronger HDIF sense, interspace is thus not merely something located between interfaces, but an emergent traversal structure produced by them.

## 5.2 Passive and Dynamic Interspace

A useful distinction within the present framework is between *passive* and *dynamic interspace*. A *passive interspace* is one in which the ordered composition of interfaces preserves the relevant relational structure without introducing significant additional transformation beyond what is already required for traversal. In such cases, the composed architecture functions primarily in a transmissive or preservative manner: it supports traversal, but does not itself contribute significant effective transformation beyond the local interface rules.

A *dynamic interspace*, by contrast, is one in which the composed interface structure contributes nontrivially to effective evolution. In this regime, traversal outcome depends not only on the local action of any one interface, but also on the relational conditions generated by their composition. A dynamic interspace may therefore filter, delay, redirect, mix, or otherwise condition traversing structure prior to emergence.

This distinction is important because it identifies cases in which the traversal architecture itself becomes physically consequential. In such settings, interspace is not merely a background interval, but part of the effective relational organization that helps determine traversal outcome. At the same time, not every ordinary geometric separation or externally identified interval need be treated as an interspace in the stronger HDIF sense. The term is most appropriate when ordered interface composition gives rise to a traversal structure with physically relevant relational consequences.

## 5.3 Encoded Relational Conditions

The possibility of dynamic interspace raises a deeper structural point: traversal outcomes may depend on *encoded relational conditions* induced by the composed interface architecture itself. These conditions need not correspond to explicit material content alone, but may instead take the form of admissibility constraints, transformation rules, symmetry breaking, environmental asymmetries, memory-bearing organization, or geometry-dependent relational structure that shapes how traversal proceeds.

This perspective is especially important for distinguishing between *effective regime* and *underlying structure*. A given interspace may appear dissipative, selective, delayed, or history-sensitive at the level of observable traversal, while those behaviors themselves arise from the deeper relational organization encoded by interface composition rather than from a distinct intervening medium or from any one isolated interface taken alone. Such encoded conditions may govern not only which forms of propagation, transformation, or admissibility are realized through the traversal architecture, but also which traversal pathways are internally accessible, externally causally exposed, or effectively available relative to the surrounding relational configuration.

## 5.4 Interspace and Sequential Interface Structure

Once composed interface architecture becomes physically consequential, traversal can no longer be described solely in terms of isolated interface actions. Instead, it must be treated as a sequential process whose effective outcome depends on the cumulative relational organization of the interfaces through which it passes.

In such settings, each interface acts not on an abstract unchanged input, but on a state already conditioned by prior relational stages. The effective behavior of traversal may therefore depend not only on the local action of each interface, but also on the order in which those actions occur and on how earlier transformations condition later ones.

This provides the natural foundation for composed interface systems in which multiple relational stages jointly determine the final outcome of traversal. The effective behavior of the system is therefore not reducible to any single interface taken in isolation, but arises from the ordered relational architecture formed by their composition.

The next section develops this idea explicitly through the concept of the *conditional relational pipeline*, in which ordered relational stages determine the effective transformation of source and geometry across sequential interface structures.

# 6 Conditional Relational Pipelines

## 6.1 From Isolated Interfaces to Ordered Architectures

The preceding sections introduced three distinct but closely related structural elements: the interface as a rule-bearing transition object, the interspace as an emergent relational domain induced by composed interfaces, and the possibility of sequential relational organization through which multiple such elements may be arranged.

To make this progression explicit, it is useful to recognize that a minimal traversal architecture already involves three analytically distinguishable components: (1) an entrance interface, defined by relational boundary conditions on the incoming side; (2) an emergent interspace, understood not as a pre-existing

region but as the relational structure induced by interface composition; and (3) an exit interface, defined by the relational boundary conditions on the outgoing side. Even in the simplest case, traversal is therefore not a single crossing event, but a structured relation between entry conditions, induced relational domain, and exit conditions.

In more general settings, these elements need not occur only once. Multiple interfaces may be composed in sequence, generating layered or nested interspace structures whose effective role is not reducible to any one local transition. The resulting traversal architecture may therefore involve repeated combinations of interface entry, interspace evolution, and interface exit, organized into an ordered relational structure.

A useful way to understand this is to consider a geometry-to-geometry interface relating two distinct Earth-bound configurations, such as a local frame associated with Tamarac, Florida and another associated with Tokyo, Japan. The entrance interface encodes the relational boundary conditions on the Tamarac side, the exit interface encodes those on the Tokyo side, and the effective traversal structure between them is not a pre-existing geometric interval, but the relational domain induced by how those boundary conditions are composed. In more structured cases, additional intermediate interfaces may be inserted, generating a nontrivial interspace whose internal organization contributes to the effective outcome of traversal.

This motivates a natural hierarchical distinction within the framework:

- interfaces, which define local relational transition rules;
- interspaces, which represent emergent relational domains induced by composed interfaces;
- and conditional relational pipelines, which represent ordered architectures formed by combining interfaces and interspaces into structured sequences of relational transformation.

The remainder of this section develops the most general of these structures: the conditional relational pipeline, in which traversal is governed not by a single interface, but by an ordered composition of relational stages whose combined action determines the effective outcome.

## 6.2 Definition of a Conditional Relational Pipeline

A *Conditional Relational Pipeline* (CRP) is defined as an ordered architecture of composed relational stages in which the effective evolution of a traversing system depends on sequentially applied relational conditions. In a CRP, the output of one stage becomes the input to the next, and the overall outcome is determined not merely by isolated local transformations, but by the structured composition of multiple relational operations.

The term *conditional* indicates that each stage of the pipeline may depend on admissibility rules, transformation constraints, environmental couplings, encoded

relational conditions, inherited state structure, or prior traversal history. The term *pipeline* emphasizes that traversal proceeds through an ordered architecture whose stages are not interchangeable in general. A CRP therefore represents the most general sequential traversal structure developed in the present framework: a composition-sensitive relational architecture in which local interface action and induced traversal structure jointly determine the effective outcome.

### 6.3 Order, Context, and Compositional Dependence

A defining feature of a CRP is that its effective behavior depends on *order*. In general, the outcome of traversing two or more relational stages need not be invariant under permutation of those stages. A preservative stage followed by a dissipative or selective stage, for example, will not generally produce the same result as the same stages arranged in a different sequence. If a dissipative stage precedes a filtering stage, the filter will act on an already altered traversing state and may transmit, suppress, or reconfigure different relational features than it would in the absence of prior dissipation. Conversely, if the filtering stage occurs first, the subsequent dissipative evolution acts only on the already selected subset of structure. The two ordered architectures are therefore not generically equivalent, even when composed of the same local elements. The relational architecture is therefore composition-sensitive rather than purely additive, reflecting the general noncommutativity of sequential operations in many physical systems [12, 13]. This can be illustrated schematically by comparing

preservation  $\rightarrow$  dissipation  $\rightarrow$  filtering

with

preservation  $\rightarrow$  filtering  $\rightarrow$  dissipation,

whose ordered sequences will not generally preserve or suppress the same relational content.

In addition to order, CRP behavior may also depend on *context*. This includes environmental couplings, interface memory, admissibility constraints, boundary conditions, or coupling asymmetries under which traversal occurs. Even when the ordered architecture is held fixed, variation in these contextual conditions may alter which relational features are preserved, transformed, suppressed, or permitted throughout the pipeline [9, 10].

Importantly, the physically relevant input to a CRP need not be exhausted by the locally visible entry variables alone. Two traversing systems may be indistinguishable under a reduced local description at the point of entry, yet still evolve differently through the same Conditional Relational Pipeline if they differ in inherited relational state, prior coupling history, or latent structural organization that becomes dynamically relevant only under the ordered traversal architecture.

In this sense, a CRP may function not merely as a sequence of transformations, but also as a discriminator of relational structure that is not fully captured by coarse local state description alone.

## 6.4 Emergent Outcomes in Composite Interface Systems

Because the ordered relational structure of a CRP conditions how successive stages act on a traversing system, such architectures may generate outcomes that are not reducible to any single interface taken in isolation. Traversing structure may be progressively filtered, reoriented, mixed, encoded, delayed, or transformed through the cumulative action of multiple relational stages, even when each local stage is individually simple. In this sense, a CRP can exhibit emergent behavior at the level of the overall traversal architecture.

This makes CRPs especially useful for modeling systems in which final state depends on more than one local transition condition or one isolated interaction. Rather than being determined by a single local transition, the effective outcome reflects the cumulative action of sequential relational organization. More generally, it provides a formal language for studying composed transition systems in which ordered relational phases jointly determine the final behavior of source and geometry.

In more structured realizations, the ordered composition of pipeline stages may determine not only the transformation of the traversing state, but also the emergence and accessibility structure of the interspace induced by the composed interface architecture itself.

## 7 Relational Synthesis: Interface, Interspace, and Pipeline

### 7.1 Governing Description in Coupled Regimes

A central interpretive principle underlying the present framework is that, in sufficiently coupled regimes, the physically relevant description of a system may be governed less by its isolated constituents than by the relational structure that constrains and updates them jointly.

In this sense, what is physically operative need not be what is ontologically prior, but rather what governs the evolution of the system once coupling becomes active. Interfaces and their ordered composition therefore serve not merely as descriptive tools, but as elements of the effective governing architecture through which source and geometry acquire their observable dynamics. In more structured cases, this compositional architecture may also induce an emergent interspace whose effective role is not reducible to any one local interface taken in isolation.

### 7.2 The Minimal Relational Architecture

The preceding sections introduced the principal structural elements of HDIF: the interface as a rule-bearing transition object, the interspace as an emergent relational structure induced by interface composition, and the conditional relational pipeline as an ordered architecture of sequential traversal. Taken together,

these elements define the minimal relational architecture required to describe transition processes that cannot be reduced to passive boundary crossing alone.

At minimum, HDIF treats traversal as involving three analytically distinct aspects:

1. a transition-support across which an interface is defined,
2. a relational rule structure that governs what is preserved or transformed across that support,
3. and the possibility of sequential composition through which effective traversal architecture may emerge.

In this sense, the minimal HDIF object is not simply a boundary, but a structured relation between support, composition, and transformation.

### 7.3 Multi-Layer Relational Organization

Within this architecture, local interface action and larger compositional structure jointly determine the effective evolution of what traverses them. The interface governs the local relational action at a transition, while ordered composition governs how those local actions accumulate, constrain, or condition one another across sequential traversal. When multiple such stages are composed, their ordered interaction may generate effective behavior that is not attributable to any one local element in isolation.

HDIF therefore provides a multi-layer relational description in which physically relevant behavior may arise simultaneously at several levels: the local interface, the induced relational structure generated by composition, and the larger sequential architecture through which traversal is staged. This layered view is especially important for systems in which outcomes depend not only on what is crossed, but on how crossing is organized over the full traversal architecture.

At higher levels of organization, the relational architecture may also condition which traversal structures become available, internally accessible, or externally causally exposed as part of the effective behavior of the system.

### 7.4 Interpretive Summary

Taken as a whole, HDIF reframes boundaries, transitions, and traversal as components of a unified relational architecture. Rather than treating boundaries as passive separators and traversal as occurring across an inert interval, the framework treats supports, interfaces, emergent interspace, and sequential order as jointly constitutive of effective physical evolution.

The significance of this perspective is not that every physical boundary must be reinterpreted as a complex interface architecture, but that such an interpretation becomes available whenever ordinary passive-boundary descriptions are insufficient. In this sense, HDIF is best understood not as a replacement for

standard treatments in regimes where they already suffice, but as a generalized relational language for describing systems in which structure, transformation, and traversal cannot be cleanly separated.

In this way, HDIF provides a principled basis for asking when effective physical behavior may be governed more by relational architecture than by isolated local constituents alone.

The next section turns from this conceptual synthesis to schematic realizations intended to illustrate how distinct interface architectures may generate qualitatively different classes of traversal behavior.

## 8 Illustrative Interface Regimes and Traversal Architectures

Where Section 7 synthesized the conceptual architecture of the framework, the present section turns to schematic realizations intended to show how distinct interface configurations may generate qualitatively different classes of traversal behavior. The purpose of this section is not to exhaust the possible realizations of HDIF, but to illustrate how the framework may be applied across a set of conceptually distinct interface configurations. The examples below are intentionally schematic. Their role is not to assert immediate physical realizability in each case, but to clarify how different interface architectures may generate different classes of relational behavior. Each example highlights a distinct phenomenon within the framework: conservative geometric matching, geometric reorientation, source transformation, emergent interspace, and composition-sensitive cumulative evolution.

### 8.1 Conservative Geometric Matching

Consider first an idealized interface that acts as a smooth geometric identification across its defining support conditions. In this case, the interface primarily relates geometry to geometry and operates in a preservative dynamical regime. Traversing structure is transported across the support without substantive distortion, dissipation, or internal reconfiguration. The interface therefore functions as a conservative gluing map or lossless coordinate transition.

This scenario represents the simplest limiting case of HDIF. Its significance lies not in physical complexity, but in providing a conservative baseline against which more structured interface behaviors can be distinguished. In this limit, the interface acts primarily to preserve relational continuity rather than to modify it.

### 8.2 Minimal Earth-Bound Geometric Reorientation

A useful limiting illustration of HDIF is a case in which the interface acts primarily as a geometry-to-geometry identification while leaving the internal structure of the traversing source unchanged at the moment of transition. Consider an

idealized interface whose support conditions relate two distinct Earth-bound local frames, such as one associated with Tamarac, Florida and another associated with Tokyo, Japan.

In the simplest conservative limit, the interface acts by re-expressing the state of the traversing source relative to the exit-side geometric frame. The physically relevant change is therefore not a modification of the source itself, but a change in the geometric relation between the source and the surrounding field structure after traversal.

Let the local effective gravitational fields on the two sides be denoted by

$$g_A(x), \quad g_B(\tilde{x}), \quad (1)$$

where side  $A$  and side  $B$  correspond to the two local frame configurations. Let the interface map  $I_H$  act schematically on position and velocity according to

$$I_H : (x, v)_A \mapsto (\tilde{x}, \tilde{v})_B, \quad (2)$$

with

$$\tilde{x} = R_H x, \quad \tilde{v} = R_H v, \quad (3)$$

where  $R_H$  denotes the effective frame-reorientation induced by the interface.

After traversal, subsequent motion is governed by the exit-side dynamics. In an idealized vacuum-like limit, one may therefore write

$$m\ddot{\tilde{x}} = mg_B(\tilde{x}). \quad (4)$$

This equation should be understood as the post-transition equation of motion in the new frame, not as a consequence of the interface map alone.

A more general case arises when environmental coupling is present after traversal. Then the effective evolution may include additional forces,

$$m\ddot{\tilde{x}} = mg_B(\tilde{x}) + F_{\text{env}}(\tilde{x}, \dot{\tilde{x}}), \quad (5)$$

or, in a simplified drag-dominated regime,

$$m\ddot{\tilde{x}} = mg_B(\tilde{x}) - \gamma\dot{\tilde{x}}. \quad (6)$$

This illustrates an important HDIF point: the same underlying interface architecture may realize different effective dynamical regimes depending on which couplings are active after traversal.

### 8.3 Dissipative or Transformative Source Filtering

Now consider an interface that acts primarily on source structure rather than geometric structure. In this case, the traversing system may be filtered, dissipated, mixed, or selectively transformed as it passes through the interface, while the relevant geometric structure associated with the interface support remains

effectively fixed. The dominant coupling class is therefore source-to-source, and the dominant regime is transformative or nonconservative.

An interface of this kind may preserve some source features while degrading or reconfiguring others. For example, the interface may selectively transmit only certain structural, energetic, or organizational aspects of the traversing system while dissipating or filtering the rest. This illustrates how HDIF distinguishes between simple transmission and transformation-bearing traversal even when no nontrivial geometry change is assumed.

The significance of this example is that nontrivial interface behavior need not require geometric distortion or dimensional mismatch. An interface may act entirely through source transformation while leaving the larger support geometry effectively unchanged. In such cases, what matters physically is not where traversal occurs, but how the interface selectively reorganizes what passes through it.

## 8.4 Emergent Interspace from Interface Composition

A different class of behavior arises when the principal traversal structure is not exhausted by any one interface taken in isolation, but instead emerges from the ordered composition of multiple interfaces. In such cases, the physically relevant domain of traversal is not a primitively given interval through which the system later propagates, but an effective relational structure induced by the composed interface architecture itself.

This provides the clearest illustration of interspace in the stronger HDIF sense. Consider a sequence of individually simple interfaces whose local boundary conditions are each relatively unremarkable when treated alone. If those interfaces are arranged in a structured composition, however, their ordered relation may generate an internally meaningful traversal domain whose accessibility, transformation properties, and causal exposure are determined by the relational structure of the architecture as a whole.

A traversing system in such a case does not merely encounter isolated local transitions. It propagates through an induced traversal domain whose effective properties are inherited from the relational organization of the interfaces that generate it. In this sense, the interspace is not a passive gap or hidden container, but an emergent relational structure produced by interface composition itself.

Importantly, the existence of such an induced traversal domain need not imply unrestricted external visibility or causal accessibility from outside the architecture. An interspace generated by ordered interface composition may be internally traversable while remaining externally restricted, geometrically occluded, or only partially exposed relative to surrounding configurations. This restricted accessibility is not introduced here as a metaphysical claim, but as a structural consequence of the relational architecture that defines the traversal system.

## 8.5 Sequential Composition and Accumulated Transformation

A final and more strongly structured class of scenario arises when multiple interfaces are arranged in sequence such that each stage acts on a state already modified by prior traversal. In this setting, the effective outcome is determined not only by local interface rules, but by the cumulative action of ordered relational updates. This is the characteristic setting of a Conditional Relational Pipeline.

Consider a sequence of interfaces arranged such that each successive layer is rotated by a small angle relative to the previous one, while remaining locally stationary with respect to its own support. A traversing extended source passing through this composed interface sequence would undergo a cumulative transformation, since the outgoing relational configuration produced at one stage becomes the incoming configuration acted upon by the next.

Even if each individual interface is only weakly transformative, the ordered composition of the sequence may generate a substantial global deformation in the traversing structure. For example, an initially coherent extended source may emerge with a progressively reoriented or spiral-like configuration, reflecting not merely repeated passage through similar layers, but the fact that each local transformation acts on a state already modified by prior traversal.

This illustrates an important structural point in HDIF: transformation need not be attributable to a single interface acting in isolation. Rather, effective behavior may arise from the sequential accumulation of locally modest relational updates, whose total effect becomes appreciable only at the level of the full traversal architecture.

The example also clarifies how history-sensitive behavior may enter without requiring explicit dissipation. If the action of later interfaces depends not only on their local rule, but also on the transformed state inherited from earlier stages, then traversal becomes history-sensitive in a minimal but physically meaningful sense. More generally, one may also consider cases in which the local interface response itself depends on prior deformation, prior orientation, or previously encoded relational conditions, thereby introducing an additional layer of path-dependent evolution.

In this sense, the configuration provides a concrete example of a system that may be simultaneously transformative, composition-sensitive, and, in an extended realization, history-dependent. It therefore highlights how even simple local interface rules, when arranged in a structured sequence, can give rise to emergent global behavior that reflects the relational architecture of traversal rather than any one local transition in isolation.

Taken together, the preceding examples illustrate that HDIF is not merely a descriptive vocabulary for interfaces, but a framework that distinguishes several structurally different classes of traversal behavior. Conservative matching, geometric reorientation, source transformation, emergent interspace, and composition-sensitive cumulative evolution all suggest that interfaces and their ordered compositions may be treated as formally representable objects rather than purely qualitative metaphors. This motivates the next step: to iden-

tify a minimal mathematical scaffold capable of representing interfaces, their composition, and the effective traversal structures they induce.

## 9 Toward a Minimal Mathematical Representation of Interfaces and Pipelines

### 9.1 Minimal Formal Ingredients

The preceding sections developed HDIF as a conceptual and structural framework and illustrated several distinct classes of traversal behavior that such a framework may admit. To indicate how these structures may be represented more formally, it is useful to introduce a minimal mathematical scaffold for the core elements of the theory. The goal of the present section is not to specify a complete dynamics, but to identify the abstract objects required to represent interfaces, their ordered composition, and the effective traversal structures they may induce.

At minimum, one may distinguish the following ingredients:

- a *support* or transition locus  $H$ , representing the boundary-like structure across which an interface is defined;
- a *state space*  $\mathcal{S}$ , representing the relationally relevant structure of the traversing system;
- an *interface map* or operator  $I_H$ , representing the rule by which states are related across the support;
- an *ordered composition structure*  $\mathcal{C} = \{I_{H_i}\}_{i=1}^n$ , representing the sequential arrangement of multiple interfaces or relational stages;
- an *effective traversal evolution rule*  $E_{\mathcal{C}}$ , representing how composed interface structure governs cumulative relational evolution;
- and, where relevant, an *accessibility structure*  $A$ , representing the relational conditions under which an induced traversal architecture is internally accessible, externally visible, or causally exposed relative to the surrounding configuration.

Taken together, these elements provide a minimal formal vocabulary for describing transition processes in HDIF. In this formulation, interspace is not introduced as a primitive mathematical domain, but may instead arise as an effective relational structure induced by the ordered composition  $\mathcal{C}$  and its associated evolution rule  $E_{\mathcal{C}}$ .

### 9.2 Interfaces, Effective Traversal, and Ordered Composition

An interface may be represented abstractly as a map or operator acting on relational states. If  $\psi_{\text{in}} \in S$  denotes the incoming state of a traversing system and  $\psi_{\text{out}} \in S'$  the outgoing state after traversal across support  $H$ , then schematically

$$\psi_{\text{out}} = I_H(\psi_{\text{in}}). \quad (7)$$

In the simplest conservative limit,  $I_H$  may act as an identity-preserving or lossless transformation between equivalent relational structures. More generally,  $I_H$  may be nonlinear, non-invertible, dissipative, state-dependent, or memory-bearing.

This representation is intentionally local:  $I_H$  characterizes the relational action associated with a given support  $H$ , without yet specifying how multiple interfaces combine into a larger traversal architecture.

For composed systems, let

$$\mathcal{C} = (I_{H_1}, I_{H_2}, \dots, I_{H_n}) \quad (8)$$

denote an ordered sequence of interfaces. Traversal through that sequence may then be represented by the composed operator

$$\Phi_{\mathcal{C}} = I_{H_n} \circ I_{H_{n-1}} \circ \dots \circ I_{H_1}. \quad (9)$$

Thus,

$$\psi_{\text{out}} = \Phi_{\mathcal{C}}(\psi_{\text{in}}). \quad (10)$$

In some cases, the full composition may admit a coarser effective description

$$\psi_1 = E_{\mathcal{C}}(\psi_0), \quad (11)$$

where  $E_{\mathcal{C}}$  is an effective traversal rule summarizing the cumulative action of the ordered architecture.

In general, ordered compositions need not commute. For two stages  $I_A$  and  $I_B$ ,

$$I_B \circ I_A(\psi) \neq I_A \circ I_B(\psi), \quad (12)$$

so traversal behavior may depend intrinsically on stage order.

### 9.3 Admissibility, History Dependence, and Relational State

If interfaces and their ordered compositions are to function as more than schematic placeholders, their associated maps should satisfy minimal admissibility conditions.

A first condition concerns *well-posedness*. For admissible input states  $\psi_{\text{in}} \in S$ , the relevant map should produce a sufficiently well-defined output state in the regime where the description is intended to apply.

A second condition concerns *preservation and controlled transformation*. In preservative regimes, one may require that selected quantities  $Q$  satisfy

$$Q(\psi_{\text{out}}) = Q(\psi_{\text{in}}). \quad (13)$$

In transformative regimes, selected features may instead evolve according to controlled modification rules.

A third condition concerns *history dependence*. In memory-bearing systems, the effective output may depend not only on the instantaneous state, but on an admissible prior history. Let  $\mathcal{H}_t$  denote a space of admissible histories on  $(-\infty, t]$ . Then one may write schematically

$$\psi_{\text{out}} = \mathcal{P}_t[\psi|_{(-\infty, t]}], \quad (14)$$

where  $\mathcal{P}_t : \mathcal{H}_t \rightarrow S'$  is a causal history-dependent map.

A fourth condition concerns *order sensitivity*. For an ordered architecture,

$$I_{H_2} \circ I_{H_1} \neq I_{H_1} \circ I_{H_2} \quad (15)$$

may hold in general.

A further issue concerns the completeness of state specification. In some systems, a reduced local state may be insufficient to determine traversal outcome uniquely. One may therefore require an extended relational specification,

$$\Psi_{\text{in}} = (\psi_{\text{local}}, H_{\text{rel}}, \Lambda_{\text{latent}}, \dots), \quad (16)$$

where  $H_{\text{rel}}$  denotes admissible prior relational history and  $\Lambda_{\text{latent}}$  denotes additional latent relational structure.

A Conditional Relational Pipeline may therefore act not only as a transformation architecture, but also as a discriminator of relational distinctions not visible in a coarse local state description alone.

## 9.4 Toy Realization: Sequentially Accumulated Relational Transformation

To illustrate how ordered interface composition can generate emergent behavior, consider a sequence of interfaces  $\{H_k\}_{k=1}^n$  acting on a traversing state  $\psi \in S$ .

Let each stage be represented by an operator

$$\psi_k = I_{H_k}(\psi_{k-1}), \quad (17)$$

with

$$I_{H_k} = R_{\hat{n}_k}(\theta_k), \quad (18)$$

where  $R_{\hat{n}_k}(\theta_k)$  denotes a rotation-like transformation through angle  $\theta_k$  about stage-dependent axis  $\hat{n}_k$ .

The total output after  $n$  stages is

$$\psi_{\text{out}} = I_{H_n} \circ I_{H_{n-1}} \circ \dots \circ I_{H_1}(\psi_{\text{in}}). \quad (19)$$

Because the axes may differ from stage to stage, these operators need not commute:

$$R_{\hat{n}_j}(\theta_j)R_{\hat{n}_i}(\theta_i) \neq R_{\hat{n}_i}(\theta_i)R_{\hat{n}_j}(\theta_j). \quad (20)$$

Thus the final state may depend intrinsically on traversal order.

Even when each stage is only weakly transformative, the cumulative composition may generate a substantial global deformation of the traversing state.

Sequential state dependence already enters because each stage acts on the state produced by previous stages. Explicit memory effects may be incorporated by allowing stage parameters to depend on prior states:

$$\theta_k = \theta_0 + k\delta\theta + \alpha F(\psi_{k-1}, \psi_{k-2}, \dots). \quad (21)$$

In that case, local interface response depends not only on stage label, but on traversal history itself.

This toy model should be understood not as a literal physical proposal, but as a compact demonstration of how HDIF can represent cumulative, order-sensitive, and history-dependent relational evolution.

## 9.5 Scope and Limits of the Present Formalization

The schematic representation introduced here, together with the minimal admissibility conditions and toy realization above, is intended only as a constrained formal scaffold. It does not by itself specify the detailed ontology of  $\mathcal{S}$ , the geometric nature of  $H$ , the physical realization of  $I_H$ , or the detailed relational structure induced by ordered composition. Those details may differ substantially depending on whether the relevant interface is geometric, material, source-bearing, memory-dependent, or sequentially composed.

Its value lies instead in showing that HDIF admits a mathematically representable architecture. Supports, interfaces, ordered compositions, and the effective traversal structures they induce can all be treated formally and may, in principle, be specified more precisely within particular physical realizations. In this sense, the present formalization should be understood as a general representational framework for future refinement.

One especially natural direction for such refinement would be the formulation of admissible constitutive response laws governing how source-bearing structure and geometric organization co-evolve across interfaces or horizon-like supports.

# 10 Physical Interpretation and Domains of Relevance

## 10.1 Interpretive Scope of the Framework

HDIF is intended as a general relational framework for systems in which boundaries, transitions, or traversal processes cannot be adequately described as passive separations alone. Its relevance is therefore not confined to a single physical domain, but extends in principle to settings where effective evolution depends

on structured interface behavior, nontrivial relational composition, or ordered sequences of transformation.

The framework is especially useful when one wishes to distinguish what is preserved, what is transformed, and what is conditioned by the architecture of traversal itself. In this sense, HDIF is best understood not as a replacement for standard descriptions where passive-boundary models already suffice, but as an extension for regimes in which transition behavior carries independent physical significance.

Its present value is methodological as much as interpretive. It offers a relational language for identifying when support conditions, interface action, ordered composition, and induced traversal structure should enter the effective physical description rather than remain implicit background assumptions. HDIF is most useful not where it displaces already successful models, but where it clarifies when a richer transition-based description is warranted.

## 10.2 Geometric and Spacetime Transition Structures

One natural domain of relevance for HDIF lies in systems where geometric or spacetime structure itself is part of what is being related across a transition. In such settings, boundary-like supports may function not merely as delimiting surfaces, but as loci across which geometric continuity, discontinuity, distortion, or transformation becomes physically meaningful. This includes cases in which the relevant transition concerns coordinate structure, curvature organization, dimensional relation, or more general geometry-to-geometry coupling.

In this context, the generalized use of the term *horizon* becomes particularly relevant. A horizon, in the present framework, is not restricted to a causal boundary in the narrow relativistic sense, but may more broadly denote a transition-support whose physical significance derives from the interface relations it sustains. This makes HDIF potentially relevant to horizon-like structures in gravitational or geometric settings where what matters is not merely the existence of a boundary, but the relational organization defined across or induced by it.

The point is not that all such structures must be redescribed in HDIF terms, but that the framework becomes useful when the physically relevant behavior depends on how geometric relations are enacted, constrained, or transformed across a support rather than on boundary location alone [1, 7, 8, 14, 15].

## 10.3 Material, Environmental, and Source-Dependent Interfaces

HDIF is equally applicable to systems in which the dominant transformation occurs not in geometry alone, but in the behavior of traversing source structure under material, environmental, or state-dependent transition conditions. In such cases, interfaces may act as filters, dissipative layers, selective transfer structures, or transformation-bearing media whose primary role is to modify source organization rather than geometric support.

This makes the framework relevant to a broad class of physical situations involving nonuniform media, dissipative passage, selective transmission, or context-dependent traversal. In such systems, the physical significance of a transition lies not solely in where a system crosses, but in how the interface and the relational architecture in which it is embedded shape the effective evolution of what passes through it [10, 11].

This domain is particularly important because it shows that HDIF does not require exotic geometric or horizon-like scenarios in order to become useful. Even in comparatively ordinary physical settings, the framework may help distinguish between simple transmission and genuinely transformation-bearing traversal.

## 10.4 Sequential and Engineered Transition Architectures

A further domain of relevance arises in systems whose behavior depends on multiple ordered transitions rather than a single isolated crossing. In such cases, the effective outcome may depend on stage order, relational composition, or layered constraints. HDIF provides a natural language for describing these architectures in terms of interfaces and Conditional Relational Pipelines.

This makes the framework potentially useful not only for naturally occurring transition systems, but also for engineered or designed architectures in which traversal outcome depends on structured sequencing. More generally, HDIF is relevant wherever relational behavior is composition-sensitive rather than reducible to a single local transformation.

Such architectures may also be relevant in cases where the ordered interface structure determines not merely traversal outcome, but the emergence and accessibility properties of the effective traversal structure induced by composition itself. In this sense, HDIF is especially well suited to systems in which the physically relevant behavior depends on how local transition rules accumulate, constrain, or condition one another across a larger traversal architecture.

These domains of relevance do not yet establish predictive closure, but they do clarify the kinds of systems in which HDIF may serve as a useful interpretive and formal starting point. The remaining question is therefore not only where the framework may apply, but what its present contribution and limits actually are.

# 11 Discussion, Scope, and Open Problems

## 11.1 What HDIF Contributes

The principal contribution of HDIF is not the introduction of a single new dynamical law, but the development of a structured relational framework for describing systems in which boundaries, transitions, and traversal processes cannot be adequately modeled as passive separations alone. In this sense, the framework contributes a conceptual and formal architecture for distinguishing among supports, interfaces, ordered compositions, and the effective traversal

structures they may induce, and for analyzing how each of these may contribute to physical behavior.

More specifically, HDIF contributes three interrelated advances. First, it treats the interface itself as a rule-bearing relational object rather than a merely geometric separator. Second, it distinguishes *dynamical regime* and *coupling class* as analytically distinct dimensions of interface behavior. Third, it extends the analysis of local transitions into ordered relational architectures through the concepts of composed interface structure, emergent interspace, and Conditional Relational Pipelines. Taken together, these elements provide a unified language for describing transition systems whose effective structure depends on more than isolated boundary crossing.

## 11.2 Scope and Present Limits

At the same time, HDIF in its present form should not be interpreted as a complete predictive physical theory. The framework does not yet specify a unique microscopic ontology, a universal dynamical law, or a domain-independent set of governing equations from which all interface behavior can be derived. Nor does it imply that every physically meaningful boundary must be reinterpreted as a nontrivial interface or composed relational architecture.

Its present scope is therefore best understood as organizational, representational, and preparatory. HDIF provides a way to identify, classify, and schematize relational structures that may become physically significant when passive-boundary descriptions prove insufficient. Whether any particular physical system genuinely requires such a description remains a matter for further formal development, model construction, and empirical interpretation.

## 11.3 Open Problems for Formal and Physical Development

Several open problems follow naturally from the present formulation. A first open problem concerns *formal specification*: how should particular interface maps, ordered compositions, and admissible relational update rules be defined in concrete physical settings? This includes the unresolved question of how relationally complete input states should be specified in cases where reduced local state descriptions may be insufficient to determine traversal outcome uniquely. The minimal mathematical scaffold introduced in Section 9 establishes a representational structure, but not yet a unique or physically grounded formal realization.

A second open problem concerns *regime emergence*: under what conditions do preservative, transformative, dissipative, or memory-bearing regimes arise from deeper relational structure? This includes the question of whether observed effective behavior should be attributed primarily to local interface action, induced traversal structure, or sequential composition.

A third open problem concerns *physical instantiation*: which known physical systems are most naturally and fruitfully described within the HDIF language? While the framework is intentionally domain-general, its scientific value will

ultimately depend on whether it can illuminate concrete classes of systems more clearly than existing passive-boundary descriptions.

A fourth open problem concerns *predictive closure*: can HDIF be developed beyond a classificatory and representational framework into a constrained formalism capable of generating distinctive, testable predictions in particular domains? This remains an open and important question for future work.

In particular, it remains open whether HDIF-style interface architectures could help organize experimentally meaningful observables associated with constitutive source–geometry response, such as phase-sensitive, transfer-function, or cross-scale consistency measures in appropriately constrained physical realizations.

A further open problem concerns *emergent accessibility structure*: under what conditions does sequential interface organization give rise to internally traversable but externally causally restricted effective traversal structure, and how should such accessibility be represented formally?

## 11.4 Interpretive Position of the Framework

HDIF is best interpreted as a structured generalization of transition analysis rather than as a replacement for standard physical descriptions in regimes where those descriptions already suffice. Its purpose is to make available a richer relational vocabulary for systems in which support, interface, ordered composition, and induced traversal structure all contribute meaningfully to effective behavior.

The framework should therefore be read neither as a purely metaphorical reinterpretation of boundaries nor as a completed physical theory. It occupies an intermediate position: a formal and conceptual scaffold intended to organize, sharpen, and eventually support more concrete physical models of transition structure where ordinary passive-separation language proves too coarse.

In that sense, HDIF is best understood as a disciplined starting point for further development rather than a final explanatory endpoint.

Its value will therefore depend not on the breadth of its language alone, but on whether it can support sharper formalization and more revealing physical application in the regimes where transition structure genuinely matters.

## 12 Conclusion

HDIF was developed in response to a simple but underexamined limitation: the tendency to treat boundaries as passive separations even in systems where transition structure itself may influence effective behavior. In place of this assumption, the present work introduced a relational framework in which boundaries may instead be treated as supports for interfaces—rule-bearing transition objects whose dynamical regime, coupling class, composed relational organization, and sequential composition may all contribute to the evolution of source and geometry across traversal.

Taken together, the framework provides a structured language for analyzing transition systems in which what happens across and through structured interface composition cannot be reduced to passive crossing alone. By formalizing interfaces, ordered compositions, and conditional relational pipelines as analytically distinct but composable elements, HDIF offers a general architecture for studying how preservation, transformation, and encoded relational conditions may shape physical behavior in systems where ordinary passive-boundary descriptions become insufficient.

The aim of the present work has not been to claim immediate predictive closure, but to establish a coherent relational scaffold from which more specific formal and physical developments may proceed. In that sense, HDIF is best understood as a framework for asking a sharper class of questions: not only what lies on either side of a boundary, but what relational structure is enacted through and by the composition of the supports that connect them. Future progress will depend on whether this relational scaffold can be specialized into concrete constitutive models and physically constrained observables in domains where passive-boundary descriptions prove insufficient.

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## **Data Availability**

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## **Declaration of Generative AI and AI-Assisted Technologies**

During the preparation of this manuscript, the author used an AI-assisted language model (ChatGPT, OpenAI) for limited editorial assistance, including language clarification and structural organization. All scientific content, mathematical derivations, analysis, and conclusions were developed, reviewed, and verified by the author, who takes full responsibility for the work.

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